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Solid-State Laser Engineering

Sixth Revised and Updated Edition

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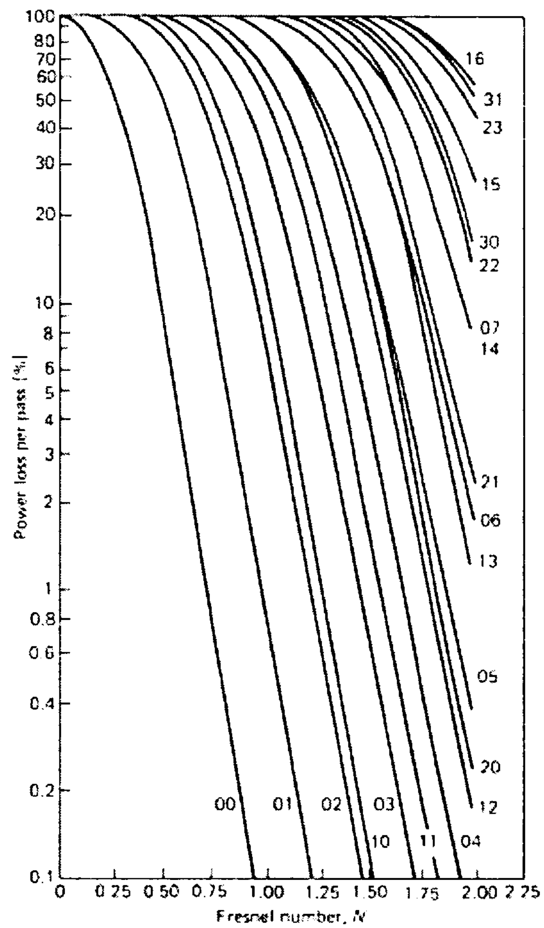

Fig. 5.10. Diffraction loss for various modes in a confocal resonator as a function of the Fresnel number [5.9]

The beam divergence of each higher order mode also increases according to the scaling law given by (5.26, 27). The increase of beam diameter and divergence of a multimode beam can be expressed by

$$\Theta = M\theta_0 \tag{5.28a}$$

and

$$D = MD_0 . \tag{5.28b}$$

where the multimode beam divergence Θ and the beam diameter D are related to the fundamental mode beam parameters θ_0 and D_0 by a factor M.

It is not sufficient to characterize a laser beam only by its divergence because with a telescope it can always be reduced. The beam property that cannot be corrected by an optical system is the brightness, i.e., the beam intensity per unit solid angle. The brightness theorem states that the product of beam diameter and far-field angle is constant

$$\theta D = M^2 \theta_0 D_0, \tag{5.29}$$

where M^2 is a dimensionless beam-quality factor and θD is typically expressed as the beam-parameter product (mm mrad). A laser operating in the TEM_{00} mode is characterized by $M^2 = 1$ and from (5.8) we obtain

$$\theta_0 D_0 = 4\lambda/\pi. \tag{5.30}$$

The value of M^2 expresses the degree by which the actual beam is "time diffraction limited" compared to an ideal TEM_{00} beam.

For an Nd:YAG laser emitting at 1.064 μm this product is $\theta_0 D_0 = 1.35$ mm mrad. An Nd:YAG laser with a low-order mode output such as TEM_{20} shown in Fig. 5.1 has a beam quality factor of $M^2 = 5$ or, in other words, the beam is five times diffraction-limited. The beam-parameter product is about 6.8 mm mrad.

Actually the output from a multimode laser rarely consists of a single higher order mode; typically the output comprises the incoherent superposition of several modes. Multimode beams composed of the superposition of modes with beam patterns, as shown in Fig. 5.1, have the property that the beam radius will retain a fixed ratio with respect to the Gaussian beam radius $w(z)$ over all distances. The multimode beam will therefore propagate with distance in the same from as described by (5.5) for a Gaussian beam [5.12]

$$W(z) = W_0[1 + (z/z_R)^2]^{1/2} \tag{5.31a}$$

where the Rayleigh range is now

$$z_R = \frac{\pi W_0^2}{M^2 \lambda} \tag{5.31b}$$

and $W(z)$, W_0 are multimode beam analogs to the spot sizes given in (5.5) for an ideal Gaussian beam. In the limit of a TEM_{00} Gaussian beam $W(z) = w(z)$, $W_0 = w_0$, and $M^2 = 1$ and (5.31) reduces to (5.5).

Because the envelope of a multimode and TEM_{00} beam change in the same ratio over distance, calculations of the propagation of a multimode beam through a resonator can first be performed for a Gaussian beam and then multiplied by $W_0/w_0 = M$ to obtain the multimode beam diameter at each point.

For lasers employed in industrial applications, the output beam is usually focused onto a workpiece. The beam quality factor M^2 determines the minimum spot size that can be achieved with a particular lens system. The spot size diameter d of a laser beam focused by a lens with focal length f is to a first approximation

$$d = f\theta, \tag{5.32}$$